Helicity asymmetries in neutrino-nucleus interactions

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Abstract

We investigate the helicity properties of the ejectile in quasi-elastic neutrino-induced nucleon-knockout reactions and consider the ^{12}C target as a test case. A formalism based on a relativistic mean-field model is adopted. The influence of final-state interactions is evaluated within a relativistic multiple-scattering Glauber approximation (RMSGA) model. Our calculations reveal that the helicity asymmetries A_l in $A(\overline{\nu}, \overline{\nu}'N)$ processes are extremely sensitive to strange-quark contributions to the weak vector form-factors. Thereby, nuclear corrections, such as final-state interactions and off-shell ambiguities in the electroweak current operators, are observed to be of marginal importance. This facilitates extracting strange-quark information from the helicity asymmetry A_l.

Key words: neutrino interactions, Glauber theory, helicity asymmetry, strangeness of the nucleon
PACS: 25.30.Pt, 24.10.Jv, 24.70.+s, 14.20.Dh

1 Introduction

Parity-violating scattering reactions can be used to probe specific nucleonic properties which remain concealed in parity-conserving processes. A subject that has gained wide interest concerns the contribution of the sea quarks to the nucleon properties such as spin, charge and magnetic moment. From the late 1990's on, parity-violating electron scattering (PVES) has become a tool for hadron physics research at electron accelerator facilities. Mirror measurements such as SAMPLE [1] at MIT-Bates, HAPPEX [2,3] and G0 [4] at JLAB, A4 [5,6] at MAMI and E158 [7] at SLAC aim at probing the strange-quark effects

in proton structure. In the first place, these collaborations focus on the strange electric and magnetic form-factors. Radiative corrections heavily complicate the extraction of the strange axial form-factor g_A^s from the data. In the analysis of the parity-violating asymmetry observed in the PVES experiments, one estimates the effect of g_A^s relying on results of deep-inelastic double-polarized scattering experiments [8,9,10,11]. The abovementioned PVES programs triggered many theoretical studies of the strangeness magnetic moment and charge radius. These calculations are performed in a rich variety of hadron models, yielding predictions for the strangeness parameters covering a wide range of values [12,13,14,15,16,17,18,19,20]. A recent review of the theoretical and experimental status can be found in Ref. [21].

An alternative method of addressing the strangeness content of the nucleon is by means of neutrino-nucleus scattering. In contrast to PVES experiments, in extracting g_A^s no radiative corrections need to be applied. Data for $(\nu, \nu'N)$ and $(\overline{\nu}, \overline{\nu}'N)$ elastic scattering cross sections were collected at BNL [22]. As carbon was used as target material, an accurate understanding of nuclear corrections is a prerequisite for reliably extracting the strange-quark matrix elements from the data. Examples of relativistic studies which address the issue of computing the nuclear corrections, are the relativistic Fermi gas (RFG) model of Ref. [23] and the relativistic distorted-wave impulse approximation (RDWIA) models of Refs. [24,25]. As absolute cross-section measurements involving neutrinos are challenging, a lot of effort has been devoted to the study of cross-section ratios. Examples include the ratio of proton-to-neutron knockout in neutral-current (NC) neutrino-nucleus interactions [24,25,26,27], the ratio of NC to charged-current (CC) cross sections [28,29] and the ratio of NC to CC neutrino-antineutrino asymmetries [24]. For these ratios, the effects of nuclear corrections nearly cancel, facilitating the extraction of possible strange-quark contributions. Other observables which do not require absolute cross-section measurements are polarization asymmetries. Recently, the helicity asymmetry A_l was put forward as a potential tool to discriminate between neutrinos and antineutrinos in NC neutrino-induced nucleon-knockout reactions off nuclei [30,31]. In this paper, we wish to point out that the quantity A_l is also very sensitive to sea-quark contributions to the vector form-factors. This is an interesting insight, since the ratios discussed in Refs. [24,25,26,27,28,29] focus on effects stemming from g_A^s. Indeed, in those ratios the axial part largely overshoots contributions of the vector form-factors. Often, the extraction of physical information from observables involving nuclei suffer from an incomplete knowledge of medium effects. In this paper it is shown that A_l remains relatively free of these ambiguities. We adopt a relativistic framework to compute the nuclear medium effects on A_l.

The outline of this paper is as follows. In Sec. 2 we present the relativistic multiple-scattering Glauber approximation (RMSGA) formalism for the description of the helicity asymmetry within NC neutrino-nucleus scattering

processes. In Sec. 3 we present our results for A_l, and pay particular attention to the influence of medium corrections and strangeness contributions. In Sec. 4 we summarize our findings.

2 Formalism

The expressions for neutrino and antineutrino quasi-elastic neutral-current (NC) reactions from nuclei which result in one emitted nucleon, $\nu(\overline{\nu}) + A \rightarrow \nu(\overline{\nu}) + N + (A-1)$, are derived in Ref. [32]. Within the one-boson exchange approximation the one-fold differential cross section reads

$$
\begin{aligned}
\frac{d\sigma}{dT_N} = \frac{M_N M_{A-1}}{(2\pi)^3 M_A} 4\pi^2 \int \sin\theta_l d\theta_l \int \sin\theta_N d\theta_N \\
\times k_N f_{rec}^{-1} \sigma_M [v_L R_L + v_T R_T + h v_{T'} R_{T'}] \ .
\end{aligned}
\tag{1}
$$

In this expression, M_N (T_N) represents the mass (kinetic energy) of the ejectile, while M_A (M_{A-1}) refers to the mass of the target (residual) nucleus. The outgoing nucleon momentum is $\vec{k}_N$, f_{rec} is the recoil factor and σ_M a Mott-like cross section. The direction of the scattered lepton (outgoing nucleon) is fixed by the angles Ω_l (Ω_N). In Eq. (1), the helicity is $h = -1$ ($h = +1$) for neutrinos (antineutrinos). Expressions for the kinematic factors $v_L, v_T, v_{T'}$ and the structure functions $R_L, R_T, R_{T'}$ can be found in Ref. [32]. The latter ones embody the effects of the nuclear dynamics. In the calculation of the responses, the basic quantity to be computed is the transition matrix element $\langle J^\mu \rangle$. Adopting the impulse approximation and an independent-nucleon picture, $\langle J^\mu \rangle$ can be expressed as

$$
\langle J^\mu \rangle = \int d\vec{r} \, \overline{\phi}_F(\vec{r}) \widehat{J}^\mu(\vec{r}) e^{i\vec{q}.\vec{r}} \phi_B(\vec{r}) \ ,
\tag{2}
$$

where ϕ_B and ϕ_F are relativistic bound-state and scattering wave-functions, and $\widehat{J}^\mu$ is the electroweak current operator. The wave functions ϕ_B are obtained within the Hartree approximation to the σ-ω model [33].

For a free nucleon, the one-body vertex function J^μ can be expressed in several equivalent forms of which some of the more frequently used ones read [34]

$$
J_{cc1}^\mu = G_M^Z(Q^2)\gamma^\mu - \frac{\kappa}{2M_N} F_2^Z(Q^2)(K_i^\mu + K_f^\mu) + G_A(Q^2)\gamma^\mu\gamma_5 \ ,
\tag{3a}
$$

$$
J_{cc2}^\mu = F_1^Z(Q^2)\gamma^\mu + i\frac{\kappa}{2M_N} F_2^Z(Q^2)\sigma^{\mu\nu}q_\nu + G_A(Q^2)\gamma^\mu\gamma_5 \ ,
\tag{3b}
$$

$$
J_{cc3}^\mu = \frac{1}{2M_N} F_1^Z(Q^2)(K_i^\mu + K_f^\mu) + i\frac{1}{2M_N} G_M^Z(Q^2)\sigma^{\mu\nu}q_\nu + G_A(Q^2)\gamma^\mu\gamma_5
\tag{3c}
$$

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with $q^\mu = (\omega, \vec{q})$ and $Q^2 = -q_\mu q^\mu$ the four-momentum transfer. The relation between the weak Sachs electric and magnetic form-factors G_E^Z and G_M^Z and the weak Dirac and Pauli form-factors F_1^Z and F_2^Z, is established in the standard fashion. However, when considering off-shell nucleons embedded in a nuclear medium, the above vertex functions can no longer be guaranteed to produce identical results. This elusive feature is known as the Gordon ambiguity and is a source of uncertainties when performing calculations involving finite nuclei [34,35,36].

The weak vector form-factors F_1^Z and F_2^Z can be expressed in terms of the electromagnetic form-factors for protons ($F_{i,p}^{EM}$) and neutrons ($F_{i,n}^{EM}$) by the conserved vector current (CVC) hypothesis

$$
\begin{aligned}
F_i^Z = & \left(\frac{1}{2} - \sin^2 \theta_W \right) \left(F_{i,p}^{EM} - F_{i,n}^{EM} \right) \tau_3 \\
& - \sin^2 \theta_W \left(F_{i,p}^{EM} + F_{i,n}^{EM} \right) - \frac{1}{2} F_i^s \quad (i = 1, 2) ,
\end{aligned}
\tag{4}
$$

with $\sin^2 \theta_W = 0.2224$ the Weinberg angle and F_i^s quantifying the effect of the strange quarks. The isospin operator τ_3 equals $+1$ (-1) for protons (neutrons). For long, the accumulated data pointed towards electromagnetic form-factors of the nucleon whose Q^2- dependence can be well described in terms of a dipole parameterization. Traditionally, these data were obtained by means of a Rosenbluth separation of elastic $p(e, e')p$ scattering measurements. New data based on polarization transfer measurements $p(\vec{e}, e')\vec{p}$ [37,38] revealed a quite different picture for $Q^2 \geq 1$ $(\text{GeV/c})^2$. The discrepancy between the electromagnetic form-factors obtained with the two techniques is an unresolved issue, but two-photon exchange processes have been shown to play a major role [39,40].

The axial form-factor can be parameterized as

$$
G_A(Q^2) = -\frac{(\tau_3 g_A - g_A^s)}{2} G(Q^2),
\tag{5}
$$

with g_A=1.262, $G = (1 + Q^2/M^2)^{-2}$ with $M = 1.032$ GeV, and g_A^s the axial strange-quark contribution.

The remaining ingredient entering Eq. (2) is the relativistic scattering wavefunction ϕ_F for the emitted nucleon. We incorporate FSI effects in a relativistic version of the Glauber model which has been dubbed RMSGA [41]. The RMSGA represents a multiple-scattering extension of the eikonal approximation and the effects of FSI are directly computed from the elementary nucleon-nucleon scattering data through the introduction of a profile function. The Glauber method postulates linear trajectories for the ejectile and frozen spectator nucleons in the residual nucleus, resulting in a scattering

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wave-function of the form

$$\phi_F(\vec{r}) \equiv \mathcal{G}\left(\vec{b}(x,y), z\right) \phi_{k_N, s_N}(\vec{r}) , \tag{6}$$

where ϕ_{k_N, s_N} is a relativistic plane-wave. The impact of FSI mechanisms on the scattering wave function is contained in the scalar Dirac-Glauber phase $\mathcal{G}(\vec{b}, z)$ [41]. The limit of vanishing FSI, i.e. the relativistic plane-wave impulse approximation (RPWIA), is reached by putting this phase to unity. The RMSGA model was successfully tested against exclusive $A(e, e'p)$ data [42,43]. The validity of the RMSGA model in the low-energy regime was tested by comparing its predictions to results from an RDWIA calculation [32]. Satisfying RMSGA results down to nucleon kinetic energies of 250 MeV were found.

The longitudinal polarization asymmetry A_l, which will be the object of discussion in this paper, is defined as the difference in yield for the two possible helicity states of the ejectile, normalized to the total differential nucleon knockout cross section:

$$A_l(T_N) = \frac{\frac{d\sigma}{dT_N}(h_N = +1) - \frac{d\sigma}{dT_N}(h_N = -1)}{\frac{d\sigma}{dT_N}(h_N = +1) + \frac{d\sigma}{dT_N}(h_N = -1)} , \tag{7}$$

where $h_N = \frac{\vec{\sigma}_N \cdot \vec{k}_N}{|\vec{k}_N|}$ denotes the helicity of the ejected nucleon.

3 Results

The primary goal of this paper is to scrutinize the impact of strange-quark contributions on the observable A_l. First, we wish to determine the degree to which A_l is affected by variations in the parameterizations for the electromagnetic form-factors and typical medium effects like FSI and off-shell ambiguities. We consider the ^{12}C target as a test case. We take RPWIA calculations as baseline results, with dipole form-factors and the current operator in its $CC2$ form of Eq. (3b).

As mentioned earlier, in Ref. [30] the helicity asymmetry A_l was put forward as a lever to discriminate between neutrinos and antineutrinos in NC reactions on nuclei. Predictions for this asymmetry were obtained in a non-relativistic plane-wave impulse approximation and results up to beam energies of 500 MeV were presented. In the GeV energy domain, any realistic model requires the inclusion of relativistic effects. In Fig. 1, we show the RPWIA predictions for A_l for beam energies ranging from 200 to 5000 MeV. Clearly, up to lepton energies of 1 GeV, the A_l has an opposite sign for $A(\nu, \nu'N)$ and $A(\overline{\nu}, \overline{\nu}'N)$. Apparently, the discriminative power of A_l dwindles when higher beam energies are considered. The antineutrino asymmetry evolves from a dominance of

$h_N = +1$ contributions at "low" beam energies to a supremacy of $h_N = -1$ ones at "higher" energies. This can be attributed to the role played by the $G_A F_2^Z$ interference contribution.

None of the results for A_l shown so far, including those of Refs. [30,31], did account for the effects of FSI. We compute these within the RMSGA model. Fig. 2 displays the effect at beam energies of 500 MeV and 1000 MeV. As can be appreciated, the global influence of FSI mechanisms on A_l is almost negligible. In the ratio A_l a strong cancellation of FSI is noticed, even at relatively low ejectile kinetic energies. This should not be considered as a trivial result, since FSI do play an important role in the corresponding inclusive cross sections [32]. Henceforth, we will concentrate on an incoming energy of ε=1000 MeV. At this energy, the neutrino scattering process can be expected to be dominated by the quasi-elastic contribution.

Another possible source of uncertainty when determining A_l may be the insufficient knowledge regarding the electromagnetic form-factors of the proton. We performed calculations with two parameterizations: the standard dipole form and the BBA-2003 parameterization of Ref. [44]. As becomes clear from the left panel of Fig. 3, both produce comparable results. Therefore, all forthcoming results use the traditional dipole for G_E^{EM} and G_M^{EM}. We also wish to estimate the role of off-shell ambiguities on the computed A_l values. To that purpose we performed calculations with all current operators of Eq. (3). As fig. 3 shows that all these current operators produce more or less equivalent results, the sensitivity of A_l to off-shell ambiguities is minor.

The helicity asymmetry A_l emerges as a robust observable, which is not burdened by a large sensitivity to medium corrections. So far, we neglected strangeness contributions to the weak vector and axial form-factors of Eqs. (4) and (5) $(F_1^s = F_2^s = g_A^s = 0)$. To quantify the impact of the axial strangeness contribution on G_A, we adopt the value $g_A^s = -0.19$. This value was extracted from an $SU(3)$-based analysis of deep inelastic double-polarized scattering experiments [8]. In addition to sea-quark effects in the axial current, there can be contributions to the Dirac and Pauli vector form-factors. A three-pole ansatz of Forkel et al. [45] resulted in the following parameterization

$$F_1^s = \frac{1}{6} \frac{-r_s^2 Q^2}{(1 + Q^2/M_1^2)^2} \ , \tag{8}$$

$$F_2^s = \frac{\mu_s}{(1 + Q^2/M_2^2)^2} \ , \tag{9}$$

with M_1=1.3 GeV and M_2=1.26 GeV [45]. The r_s^2 and μ_s predicted by various hadronic structure models are summarized in Table 1. The list is not exhaustive. There is a tendency towards a mildly negative strangeness magnetic moment ($\mu_s \approx -0.3 \ \mu_N$), and a small negative strangeness radius ($r_s^2 \approx$

-0.01 fm^2). However, all PVES experiments performed so far suggest a positive value for μ_s. In our investigations we will use the r_s^2 and μ_s from the vector meson dominance (VMD), the KΛ, the Nambu-Jona-Lasinio (NJL) and the chiral quark soliton (CQS(K)) model. These values are selected as we find them representative for the full range of values regarding the strangeness parameters.

In Fig. 4, the proton Dirac F_1^Z and Pauli F_2^Z NC form-factors are shown for various strangeness parameters F_1^s and F_2^s. This figure reveals that mainly F_1^Z is affected. Indeed, the VMD model predicts a Dirac form-factor that overshoots the non-strangeness and other model predictions by a factor of about three. In addition, a sign switch in F_1^Z appears in the "NJL" and "CQS" models. Variations in the Pauli form-factor however are less pronounced due to its large absolute value. Thus, one can expect that mainly variations in r_s^2 will be reflected in the helicity asymmetry.

Fig. 5 shows our predictions for the helicity asymmetry at $\varepsilon=1000$ MeV for both proton and neutron knockout. The results contained in Figs. 1, 2 and 3 reveal that neutrinos are extremely selective with respect to the helicity of the ejectile. As a consequence, one can expect that any strangeness contribution will nearly cancel in the ratio of Eq. (7). The helicity preference is less outspoken for antineutrinos. Hence, antineutrinos represent a better lever than neutrinos when it comes to probing strange-quark contributions through the observable A_l. For both protons and neutrons, the introduction of a non-zero g_A^s does not substantially alter the baseline results (denoted as RPWIA in the figure). The introduction of non-zero strangeness radius and magnetic moment, on the other hand, seriously affects the ratio between $h_N = +1$ and $h_N = -1$ ejectiles. The largest deviations emerge using the predictions of the VMD model ($r_s^2 > 0$). In any case, the overall impact of F_1^s and F_2^s on the helicity asymmetry is substantially larger than the effect caused by FSI mechanisms, off-shell ambiguities and g_A^s. As can be inferred from Fig. 5, the strange contribution to the weak vector form-factors has a comparable impact on the A_l for protons and neutrons, but acts in opposite directions. This is another illustration of the well-known feature that in hunting sea-quarks in neutrino or PVES reactions, it is essential to discriminate between protons and neutrons. Indeed, the effects stemming from the sea quarks tend to cancel when summing over the proton and neutron cross-sections.

The effect of varying r_s^2 and μ_s separately is studied in Fig. 6. In the right panel, we investigate the effect of varying μ_s at $r_s=0$. Not surprisingly, we see that changing μ_s has a relatively modest effect on the helicity asymmetry. Indeed, from Fig. 4 one can infer small variations in the weak Pauli form-factor. The largest changes in A_l are induced by variations in the strangeness radius r_s^2.

4 Conclusions

We have studied the helicity properties of the ejectile in quasi-elastic neutrino-induced nucleon-knockout reactions. Results for ^{12}C have been presented for a wide range of (anti)neutrino energies. In $A(\overline{\nu}, \overline{\nu}'N)$ processes, the helicity asymmetry is found to be very sensitive to strangeness contributions in the weak Dirac and Pauli form-factors. Extraction of strange-quark information from A_l is facilitated by the fact that nuclear structure effects, such as final-state interactions, form-factor parameterization and off-shell ambiguities do not affect the asymmetry. Moreover, strangeness variations in the vector form-factors largely overshoot effects stemming from the axial part.

Acknowledgements

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Fig. 1. The helicity asymmetry as a function of T_p for proton knockout from ^{12}C at six beam energies. The left (right) panel is for neutrinos (antineutrinos).
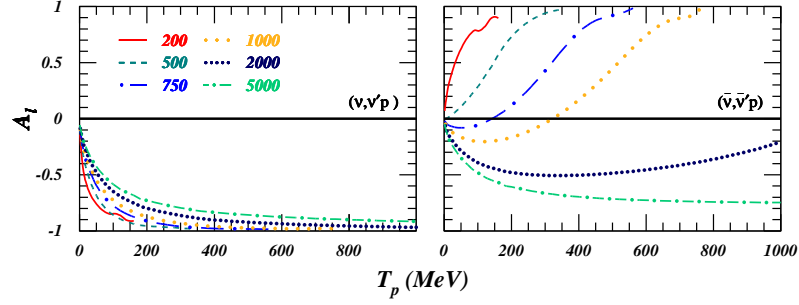

Fig. 2. The effect of FSI mechanisms on the helicity asymmetry at 500 MeV and 1000 MeV beam energies. The solid (dashed) line shows the RPWIA (RMSGA) predictions.
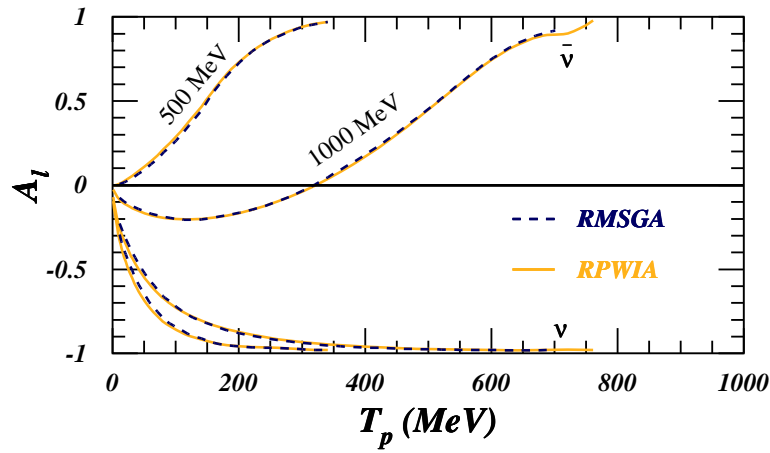

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Fig. 3. The helicity asymmetry A_l as a function of the proton kinetic energy at ε=1000 MeV as computed in an RPWIA approach. The left panel illustrates the effects stemming from the ambiguities in the electromagnetic form-factors: the solid (dashed) line shows the RPWIA results obtained with the dipole (BBA-2003) parameterization. In the right panel the role of the off-shell ambiguities is studied. The solid, dashed, dot-dashed curves are obtained with the CC2, CC1 and CC3 prescription, respectively.
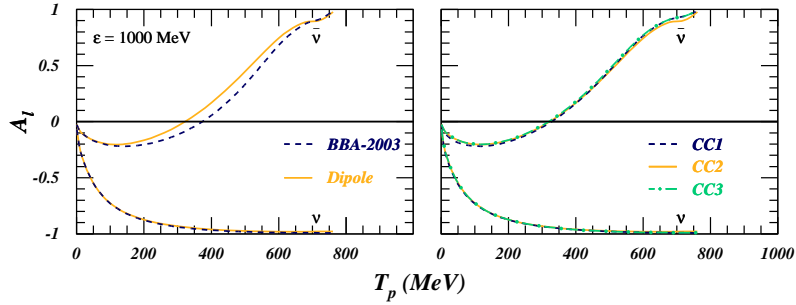

Table 1
Predictions for r_s^2 and μ_s in various hadron models.

Model	Ref.	$\mu_s(\mu_N)$	$r_s^2(\text{fm}^2)$
VMD	[12]	-0.31	0.16
$K\Lambda$	[13]	-0.35	-0.007
CBM	[14]	-0.1	-0.011
Hybrid	[15]	-0.3	-0.025
Chiral Quark	[16]	-0.09	-0.035
NJL	[17]	-0.45	-0.17
Skyrme	[18]	$-0.13 - -0.57$	$-0.1 - -0.15$
Disp. Rel.	[19]	-0.28	0.42
CQS (π)	[20]	0.074	-0.22
CQS (K)	[20]	0.115	-0.095

Fig. 4. Sensitivity of the proton Pauli and Dirac neutral-current vector form-factors to strange-quark contributions. The solid line represents the form factors in the absence of any strangeness contribution. The dashed, dot-dashed, long-dotted and short-dotted curves include non-zero strangeness contributions according to the prediction of four different hadron models: VMD [12], KΛ [13], NJL [17] and CQS model [20] respectively.
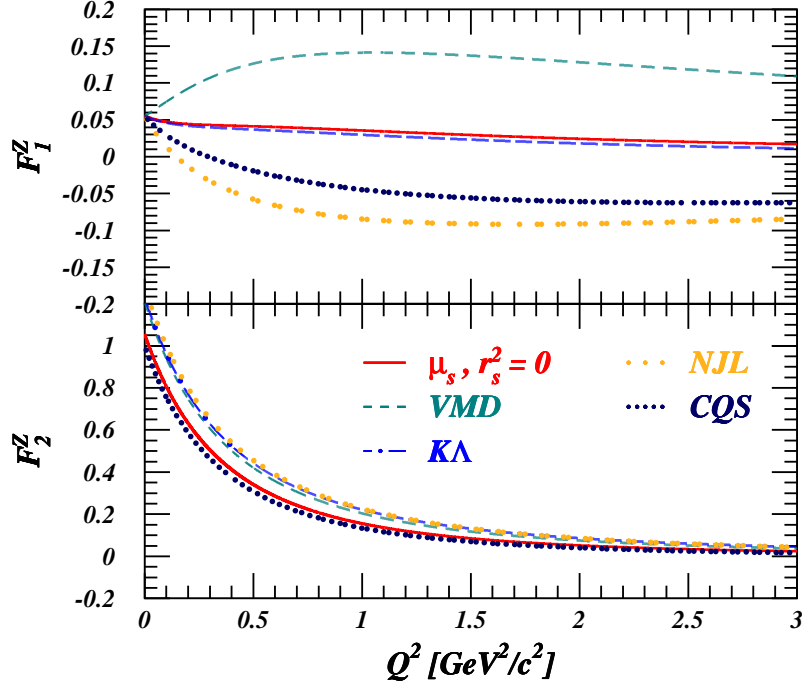
Fig. 5. Influence of sea-quarks on the helicity asymmetry at ε=1000 MeV. The left panel shows the asymmetry for antineutrino-induced proton knockout on ^{12}C, whilst the right one shows the asymmetry for antineutrino-induced neutron knockout. The solid curve represents the RPWIA results without strangeness. The other curves correspond to different strangeness parameterizations: $g_A^s = -0.19$ (dashed), VMD (long dot-dashed) [12], KΛ (long-dotted)[13], NJL (short-dotted)[17] and CQS (short dot-dashed)[20].
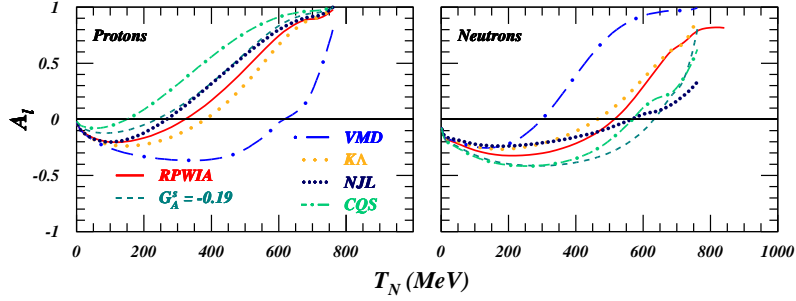

Fig. 6. The helicity asymmetry for antineutrino-induced proton knockout at ε=1000 MeV. The solid line shows the RPWIA predictions with $g_A^s = -0.19$. The left (right) panel gives the influence of varying strangeness radius (magnetic moment).